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Modelling of uniform micron-sized metal particles production using harmonic mechanical excitation

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Abstract

A novel method combining the harmonic mechanical excitation and micron-sized nozzle was proposed to prepare metal particles with micro size, good sphericity and narrow diameter distribution. A numerical model was developed to show more detailed information about the dynamic behaviours of the micron-sized metal droplet generation. The classical Rayleigh's jet linear instability theory and a Bernoulli equation were reviewed. The frequencies for uniform droplet production were predicted by using the classical linear instability with nozzle of diameters small down to 5 μm and spray pressure up to several MPa. The simulation results also show that adjacent micron-sized droplets were too close and easy to merge with each other, indicating the droplet charging process was necessary to prevent droplets merging. The proposed method was hoped to develop into a novel micron-sized metal particles preparing method with high productivity and uniformity.

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Keywords: Metal droplet; Mechanical excitation; Micron-sized nozzle; Simulation

1. Introduction

The metal powders with small size, good sphericity and narrow diameter distribution are very important in many industry applications such as metal parts 3D printing (Vaezi et al., 2013), powder metallurgy (Vajpai and

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Nomenclature

ρ_l	liquid density
μ	is the viscosity of the liquid
d_j	jet diameter
d_0	nozzle diameter
d_d	droplet diameter
F_{vol}	volume force
f	vibration frequency
g	gravity vector
h_0	thickness of the nozzle plate
P_l	pressure inside crucible
R_j	jet radius
v_j	jet velocity
v_0	liquid velocity in the nozzle
V	velocity vector
We	Weber number

Ameyama, 2013), advanced surface mount technology (SMT) (Abtew and Selvaduray, 2000). At present time, uniform metal droplet is mainly prepared on a large scale by atomization combined screen process methods. The uniform metal powder produced by the ordinary atomization is always larger than 30 μ m because it is very difficult to sieve metal powders with micro size. How to prepare micro-sized uniform metal powders on a large scale remains as a challenge.

Uniform droplet spray is another technology to produce uniform spherical metal powders. Due to its ability of producing high uniform size and relative high production rate, this technology has been employed to produce BGA ball with strictly size distribution requirement for advanced electronic packaging. This technology excited a laminar liquid jet by a harmonic mechanical excitation to be broken into metal droplets with great uniformity. This phenomenon was first described theoretically by Lord Rayleigh and known as the Rayleigh linear instability theory (Stutt et al., 1878). This theory has been unitized in cell separation, inkjet printing, vibrating spray granulation, etc. The Rayleigh breaking behaviors of jet with 0.01~1 mm diameter has been thoroughly investigated. The Rayleigh breaking behaviors of jet with 0.1~10 μ m diameter has being become the research focus in recently. However, the process window and breaking behaviors of metal jet with micro size have not been studied.

At present time, owing to the development of micromechanical processing techniques like etching, microultrasonic machining and EBM methods (Masuzawa, 2000), micro and nano-sized silicon or glass nozzle can be successfully prepared. Therefore, it is possible to combine the uniform droplet spray technology with micro sized nozzle to develop a novel micron-sized metal particles preparing method with high productivity and high uniformity.

In present paper, a novel method combining the harmonic mechanical excitation and silicon nozzle was proposed to generate micron-sized uniform metal droplets. The theory issues about the micro-sized metal jet spray and breaking was discussed by using both analysis and numerical method. A basic understanding of micro-sized metal droplet generation behaviours was discussed and the parameters combination for micron-sized uniform metal droplets production was found.

2. Principle of uniform micro-sized metal droplet generation and numerical method

The schematic diagram of metal jet generator was shown in Fig. 1(a). The main component of the droplet generator of a crucible with a small nozzle at its bottom and the heater located outside. A pressure inlet and an actuator combined by a piezoelectric ceramic and vibration rod on the crucible top. Metal was melted in the crucible by the heater, and then spray from the small nozzle. The actuator generated a mechanical vibration, which was transferred into the metal liquid and finally excited the metal jet to break.

A 2D axi-symmetric model was established to simulate the metal jet spray and breakup process. Due to the large change of dimension from the crucible area to the nozzle, the gradually changing unstructured grid was used to mesh the liquid domain of crucible for balancing the computational accuracy and efficiency. Then the fine structure grid was used to mesh the nozzle area and the air domain to obtain high simulation accuracy, as shown in Fig. 1(b).

In our simulation, some assumptions are made: (1) the metal droplet ejection is taken as an isothermal, incompressible and unsteady flow; (2) assuming the inside surface of nozzle is very smooth and the influence of surface roughness on the jet spray can be ignored. (3) the oxidation on the jet surface is ignored. The continuity and momentum conservation equations for the jet spray are described by equation (1) and (2), respectively (Batchelor 2000). The surface tension is interpreted as a continuous, three-dimensional effect across free surface and incorporated as a localized volume force \mathbf{F}_{vol} , as shown by the last term on the right-hand side of Eq. (2):

$$\nabla \cdot \mathbf{V} = 0, \quad (1)$$

$$\frac{\partial \mathbf{V}}{\partial t} + \nabla \cdot (\mathbf{V}\mathbf{V}) = -\frac{1}{\rho_l} \nabla p_l + \frac{\mu}{\rho_l} \nabla \cdot (\nabla \mathbf{V} + \nabla \mathbf{V}^T) + \mathbf{g} + \frac{1}{\rho_l} \mathbf{F}_{\text{vol}} \quad (2)$$

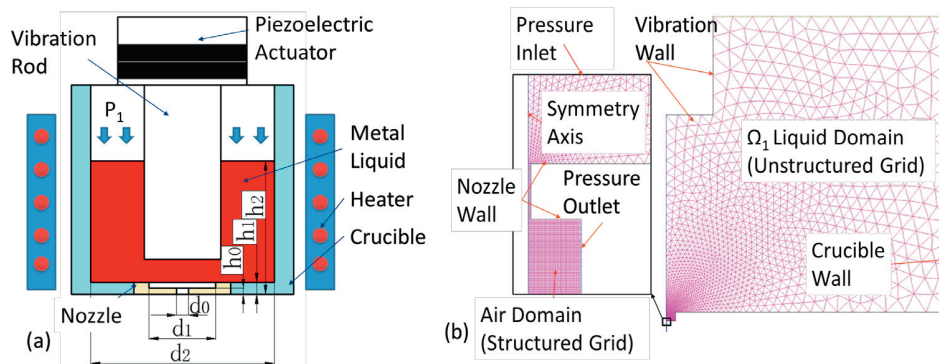


Fig. 1. (a) Schematic diagram of micro-sized droplet generator and (b) computational mesh.

In the present paper, VOF method was employed to solve above equations and the simulation process was conducted by using the FLUENT® software.

The material properties of Sn-40wt.%Pb alloy and nitrogen ambient are listed in Table 1.

Table 1. Properties of Sn-40wt.%Pb alloy and nitrogen ambient.

Material	Melting point of metal T_m (K)	Density of liquid metal ρ_l (Kg/m ³)	Surface tension of liquid metal σ_l (N/m)	Kinetic viscosity of liquid metal μ_l (Pa.s)
Sn-40wt.%Pb	456	8474.4	0.494	0.0013

Before simulation process, parameters combination of the spray pressure, the nozzle diameter and the vibration frequency for the uniform droplet generation should be first analyzed. Laminar jets can be broken into droplets because the surface energy of a liquid segment is larger than that of a liquid droplet with the same volume. Generally, the liquid will be broken randomly because the disturbance on the jet surface may be induced by the small disturbance in the nozzle that caused by the nozzle roughness or liquid contaminated. Rayleigh found that laminar jets can be broken into uniform droplet stream by exciting at a given frequency of disturbance (Stutt, Rayleigh et al. 1878). This disturbance is significantly larger than the small random disturbance on the inside of the nozzle. He showed that the radial disturbance on the circumference of jet, which was imposed by an extra

disturbance, grew exponentially as it travel down the stream and describe this process using a linear instability theory. In this case, the wavelengths of the disturbance should be larger than the circumference of the stream.

The document (Scheider and Hendricks, 1964) about the jet breaking showed that a wave number of vibration ranging from approximately $3.5d_j$ to $7.5d_j$ can also break jet into uniform droplet stream. Therefore, the upper and low boundary of the disturbance frequency for generating uniform droplets can be estimated as:

$$f_{upper} = v_j / (3.5d_j); \quad f_{low} = v_j / (7.5d_j) \quad (3)$$

With certain nozzle diameter, the relationship between vibration frequency and spray velocity can be found by using above equations. However, the spray velocity is not a parameter that can be controlled directly. It was mainly determined by the applying gas pressure. Therefore, the relationship between the spray pressure and the velocity should be obtained firstly.

In our calculation, the Bernoulli equation (Benedict, 1977), as shown in Eq. (4), can be used to solve the velocity nozzle v_0 when the d_0 and the spray pressure are given. This equation also takes the nozzle and crucible structures into consideration.

$$\frac{P_1}{\rho_l g} + \frac{\alpha_2 V_2^2}{2g} + h_0 + h_1 + h_2 = \frac{P_0}{\rho_l g} + \frac{\alpha_0 V_0^2}{2g} + \frac{32\mu d_0^2 v_0 (h_0 + h_1 + h_2)}{\rho_l g (d_0^4 + d_1^4 + d_1^4)} + K_1 \frac{v_1^2}{2g} + K_2 \frac{v_0^2}{2g} \quad (4)$$

$$\left(K_1 = 0.5 \left(1 - \frac{d_1^2}{d_2^2} \right), K_2 = 0.5 \left(1 - \frac{d_0^2}{d_1^2} \right) \right),$$

where h_0, h_1, h_2 are shown in Fig. 1. α_0 is the experiment coefficient and always is equal to 1.05 in the calculation..

The velocity nozzle v_0 can be solved as equation (5). The jet velocity v_j can be deduced by considering the difference of the nozzle diameter and jet diameter: $v_j = v_0 d_0 / d_j$. The jet diameter can be considered as 0.95 times the nozzle diameter. Therefore, the jet velocity is taken as 1.05 times the liquid velocity in the nozzle.

$$v_0 = \frac{-B + \sqrt{B^2 + 4AC}}{2A} \quad (5)$$

$$A = \frac{\rho}{2} \left(\alpha_0 + K_2 + K_1 \frac{d_0^4}{d_1^4} \right) B = 32\mu d_0^2 \left(\frac{h_0}{d_0^4} + \frac{h_1}{d_1^4} + \frac{h_2}{d_2^4} \right) C = P_1 + \rho_l g (h_0 + h_1 + h_2).$$

A non-dimensional number We number is always used to characterize the relative importance of the fluid's inertia compared to its surface tension, $We = \rho_l v_j^2 d / \sigma$. The published documents (van Hoeve, Gekle et al. 2010) showed that the $We > 4$ for forming a jet. Otherwise, the droplet will generate in dripping regime, dripping down with a huge diameter. But if the jet velocity is too large, $We_g = We \rho_l / \rho_g < 0.2$ the jet breakup transfer to wind-induced breaking regime. In this model, the jet breaks into droplets with a wide size distribution.

For finding the process window for micro-sized droplet generation, the droplet formation regimes were first calculated with nozzle diameter ranging from 0.1 μm to 100 μm . As shown in Fig. 2, all lines are obtained based on the properties of molten liquid of tin-lead alloy at 572K. It clearly shows that the minimum jet velocity for achieving the jetting regime is increased rapidly when the nozzle diameter decreases.

The strength of nozzle plate determined the spray pressure and further determined the exciting frequency for uniform droplet stream generation. In our design, we employ the monocrystalline silicon to manufacture the micro-sized nozzle by using the plasma etching process. Due to the high pressure in the crucible may crack the nozzle plate. The mechanical strength of the nozzle plate is an important factor to determine the velocity of the jet. The silicon plate was first etched to form a thin silicon film for manufacturing the small nozzle hole easily. This thin film is easy to deform or even break under the pressure. According to the classic theory of the symmetrical bending

of circular plates, the maximum tension locates in the edge the nozzle plate, as shown in Fig. 1 and expressed by Eq. (7) (Timoshenko and Woinowsky-Krieger 1959). According to Eq. (6), the maximum pressure that the nozzle plate can be achieved is increased as h_0 increases.

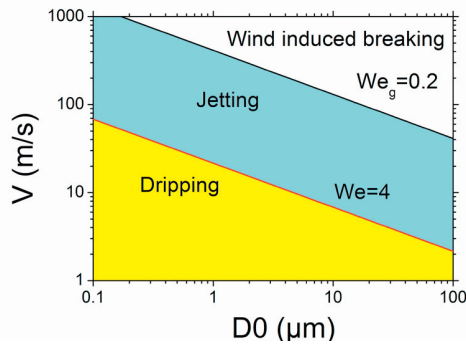


Fig. 2. Classification of droplet formation regimes as droplet generated from nozzle diameter D_0 with jet velocity v_j .

$$(\sigma)_{\max} = \frac{3}{16} \frac{P_1 d_1^2}{h_0^2} \quad (6)$$

Because the maximum jet velocity must be larger than the jetting regime low boundary to form a laminar jet, the minimum thickness is existed at each nozzle diameter. The calculation results shows that the minimum thickness is not found with $d_0=0.5$ and $0.1 \mu\text{m}$ when h_0 ranges from 1 to $500 \mu\text{m}$, indicating that droplets are generated in dripping regime when $d_0=0.5$ and $0.1 \mu\text{m}$ and thickness less than $500 \mu\text{m}$. When d_0 increases to $1 \mu\text{m}$, a nozzle with diameter of $1 \mu\text{m}$ and aspect ratio of 100 should be manufactured. When the d_0 increases to $2 \mu\text{m}$ or larger, the thickness of nozzle plate is reduced to small than $30 \mu\text{m}$, that is possible to be manufactured.

After finding out the minimum thickness of nozzle plate, we choose the h_0 of $50 \mu\text{m}$ to calculate the vibration frequency for uniform droplet stream generation as a function of spray pressure ranging from 5 KPa to 40 MPa with $d_0=5 \mu\text{m}$, as shown in Fig. 3. It can be seen that there is a low pressure boundary for generating laminar jet. The critical pressures approximate 1.4MPa as $d_0=5$.

3. Simulation results

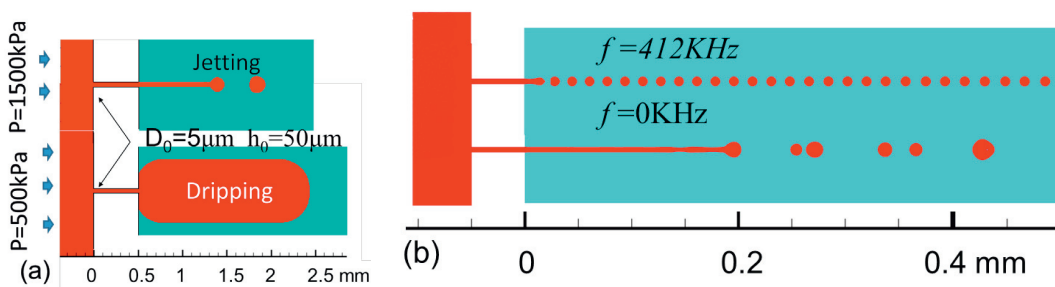


Fig. 4. Simulation results of droplet generation in jetting regime with $d_0=5 \mu\text{m}$: The metal jet breakup with vibration frequency of (a) $f=0 \text{KHz}$ and different pressure and (b) $P=1500 \text{Kpa}$, $f=0 \text{Hz}$ and 412KHz , respectively.

Fig. 4(a) shows the simulation results of droplets generation in dripping and jetting regime as $d_0=5 \mu\text{m}$. When the spray pressure is 500 KPa, as shown in Fig. 4(a), which is small than the critical pressure shown in Fig. 3. droplets

with huge diameter was generated through the small nozzle at a very slow rate. As the spray pressure is larger than the critical pressure, a laminar jet was generated. According to Fig. 3, when the spray pressure is 1500 KPa and the d_0 is 5 μm , the average frequency of f_{upper} and f_{low} of 412 KHz is chosen for uniform droplet stream generation. As shown Fig. 4(b), the uniform droplet stream is obtained as vibration frequency is 412 KHz. The droplet initial velocity is high to 9.6 m/s, which makes it is possibility to obtain a high cooling rate and further to obtain fine microstructure. The droplet diameter is about 9.6 μm , this results very closes to the droplet diameter of 9.45 μm which is calculated according to classical Rayleigh's jet linear instability theory: $d_d = d_j(1.5u_j/(d_j f))^{1/3}$ (Tseng et al, 2011). The comparison of the simulation droplet diameter with that of analysis results shows the accuracy of the simulation result.

4. Conclusions:

- (1) A novel method combining the harmonic mechanical excitation and micron-sized nozzle was proposed to prepare micro-sized uniform metal powder with high productivity and high quality. A 2D axi-symmetry model was proposed to show more detailed information about the dynamic behaviours of the micron-sized metal droplet generation.
- (2) The classical Rayleigh's jet linear instability theory and a Bernoulli equation were reviewed to determine the combination of spray pressure, nozzle size and vibration frequency for uniform droplet generation. The relationship between the nozzle thickness and the spray pressure was analyzed to find out h_0 for generating droplet at jetting regime.
- (3) The uniform droplet stream was successfully simulated by using 5 μm diameter nozzle, 1500KPa pressure and a sinusoid vibration with frequency of 412 KHz. The uniform droplets with 9.6 μm diameter, which closed to the droplet diameter of 9.45 μm obtained from classical Rayleigh's jet linear instability theory, showing the accuracy of the simulation result.

Acknowledgments

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